Qanats Ameliorate Impacts due to the desertification of the libyan sahara

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By

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Abstract

This study looks at the city of Germa within the Fezzan region of Libya. The city is located at the base of an escarpment and is surrounded by sand due to the hyper-arid environment. Understanding the past and how this area developed give perspective on how people are living there now. This study focuses on the Late Pleistocene and Early Holocene when there were periods of humidity and aridity. The cause for these fluctuations could be the result of planetary behaviors and cycles influencing the solar radiation upon Earth. The periods of humidity were known as a Green Sahara or African Humid Period. During the last humid period, large lakes existed that eventually disappeared leaving underground water sources that are still utilized today. When the water disappeared and the land became arid, most people migrated. One civilization, the Garamantians, not only stayed but also thrived. Once known as pastoral farmers, the Garamantians established an empire centered on agriculture, trading, and slavery. Much of their culture came from Egypt or Persia with Roman influences. They adopted the Persian foggara technology, which consists of a sub-horizontal underground tunnel that uses gravity to transport water for irrigation. The eventual decline of the water table led to the demise of the Garamantian Empire. Today, the foggara is referred to as a qanat and even though they are still utilized, motorized pumps are replacing them. The use of pumps, however, overdraws the water and without a source of replenishment, groundwater sources are becoming depleted.

INTRODUCTION

Across North Africa, the climate experienced broad variability during the Late Pleistocene and Early Holocene. The arid desert lands of the present-day Sahara were not always as dry as they are today. For example, beginning in the Pliocene and continuing up until the Early Holocene, there were large lakes such as Mega Chad and Mega Fezzan. These lakes were formed when the geologic and tectonic activity created basins which filled with water during humid periods, known as a Green Sahara. Over time, climatic conditions fluctuated between humid and arid periods which affected the size and longevity of these lakes. During the last Green Sahara (11,000 to 5,000 BP), animals and people spread onto a Sahara Desert that was wet and contained rivers (Garcea, 1997). Evidence that people and animals were present during this time is found in the rock carvings within caves and the walls of valleys that depict people and various animal species. In the Middle to Late Holocene, the climate became drier and life became more problematic than in the past. Most of the people living on the Sahara were no longer able to find water for drinking or for their crops and livestock. The result was depopulation from 5300 to 3500 BCE as people returned to secure sources of water, such as the Nile River (Schwartz and Ibaraki, 2011).

Not all people leave an area when the environment begins to change and the Garamantes are a good example. About 3000 years later, the Garamantians, located within the Fezzan region of Libya, were able to tap groundwater resources when they faced desertification of the land around them. They accomplished this by utilizing a water extraction technology known as qanats. The earliest use of qanats originated in Persia more than 2000 years ago (Cressey, 1958). The technology then likely spread to the Fezzan region along the trade routes with Egypt (Wilson, 2005). This area of Fezzan was home to pastoral people who established a powerful and organized settlement that would later be known as the Garamantian Empire (Wilson, 2005). The Garamantians were an innovative civilization through their use of qanats. Though they were also peaceful herders focused on settled agriculture, they were also brutal because of their reliance on slavery for qanat construction. This study offers parallels, which can be drawn to the problems experienced today such as coping with an arid environment, groundwater depletion, and environmental changes. This study can provide insight as to how to find solutions to these problems or what to expect in the future.

Study Design and Physical Setting

The methods utilized for this study involve the compilation of the results of research in peer-reviewed literature. Various sources were used in order to determine the history of past Saharan climates of Germa within the Fezzan area of Libya and how forces influenced the climate. These forces contributed to a complex climate that saw the Sahara turn from a wet savannah during periods of humidity to the more familiar desert form during dry periods. Of particular interest to this study is how the Garamantian Civilization adapted to dry conditions using qanat technology to sustain their irrigated agricultural practices for more than a millennium. With this technology, the Garamantes were able to exploit the groundwater stored within aquifers at the base of the Messak Settafet escarpment, as surface water became scarce.

Multiple databases were searched for peer reviewed articles such as JSTOR, ResearchGate, and The Ohio State University Libraries catalogues. Articles chosen contained information regarding qanats, paleoclimate in Africa, and other key words that are pertinent to this thesis. The information from many authors contributed to the data gathered and presented in the thesis. Material from Drake et al. (2008) contributed to the discussion of the mega lakes in northern Africa that once covered huge areas. Information regarding the topography, lithology, and geomorphology of the escarpment came from Perego et al. (2011) and Garcea (1997). Keys (2004) provided information on the Garamantes, while Maslin and Christensen (2007) were the source of information on the paleoclimate and factors influencing it such as the Milankovitch cycles. Schwartz and Ibaraki (2011) discussed issues surrounding the declining groundwater today. A variety of additional papers provided useful information to support these topics. This differs from the qanat section, which is a compilation of various authors providing individual facts.

The conduct of research for this thesis involved the review of source material outside of the study area in order to see a bigger picture and gain perspective of how the study area compared. The focus then shifted to the sources and information that pertained to the specific study area. Both sources of information helped to understand the relationship between people and their dependence on water.

Ultimately, the information reviewed for this thesis can be evaluated to provide insight and answers to the problems regarding water today and address solutions to current areas facing desertification. For example, wells and motorized pumps are unsustainable since they can extract large quantities of groundwater and contribute to groundwater decline in arid locations across parts of Asia and Africa. These consequences are covered in many articles. Studying these consequences and reflecting on the needs of humanity could lead to creative problem solving in order to find solutions. Due to the repetitive nature of the orbital factors such as the Milankovitch cycles, it is possible that similar humid and arid climatic conditions will repeat over long time-scales. The more concerning issue is global climate change due to human influence. These apparently unavoidable changes look to be making desert lands hotter and drier. Knowing how these conditions were dealt with in the past by studying the information contained within the articles, can help prepare and address those conditions within the present and future.

Location and Topography

The area of interest for this study is the city of Germa, located within the region of Fezzan, a part of the southwestern edge of the country of Libya, which composes a small portion of the continent of Africa and is found within the present-day Sahara (Figure 1). The Landsat image

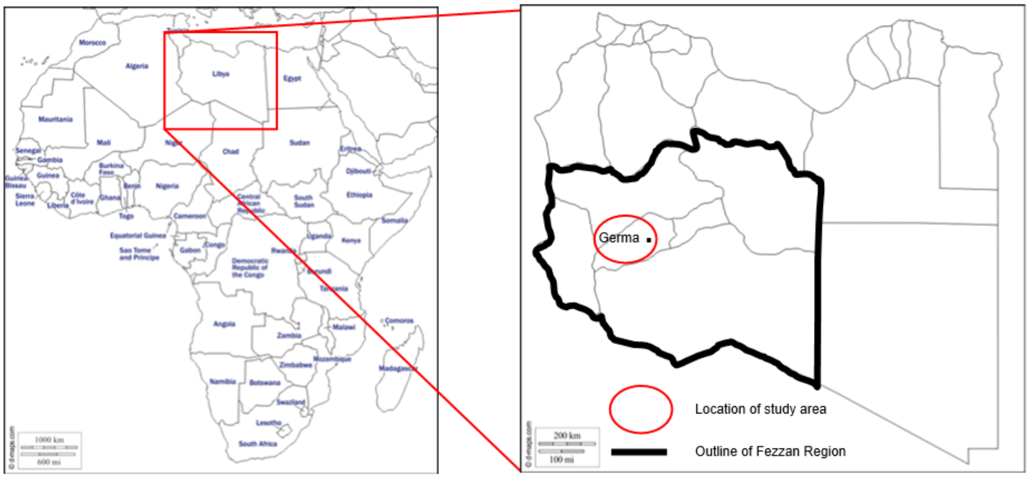

Figure 1. The focus area is located within the Sahara Desert and surrounds the present-day city of Germa in the southwestern Fezzan Region of Libya in Africa. Sources from left to right https://d-maps.com/carte.php?num_car=4339&lang=en and https://d-maps.com/carte.php?num_car=4723&lang=en.

(Figure 2) shows a large escarpment, known as the Messak Settafet. The figure shows the escarpment is distinguished by a steep slope generally facing west, towards the Wadi al Ajal and Ubari Sand Sea and a gentler slope on the backside. This crescent shaped escarpment is about 250 km long and 70 km wide (Garcea, 1997). The structure is a sandstone bedrock massif dating back to

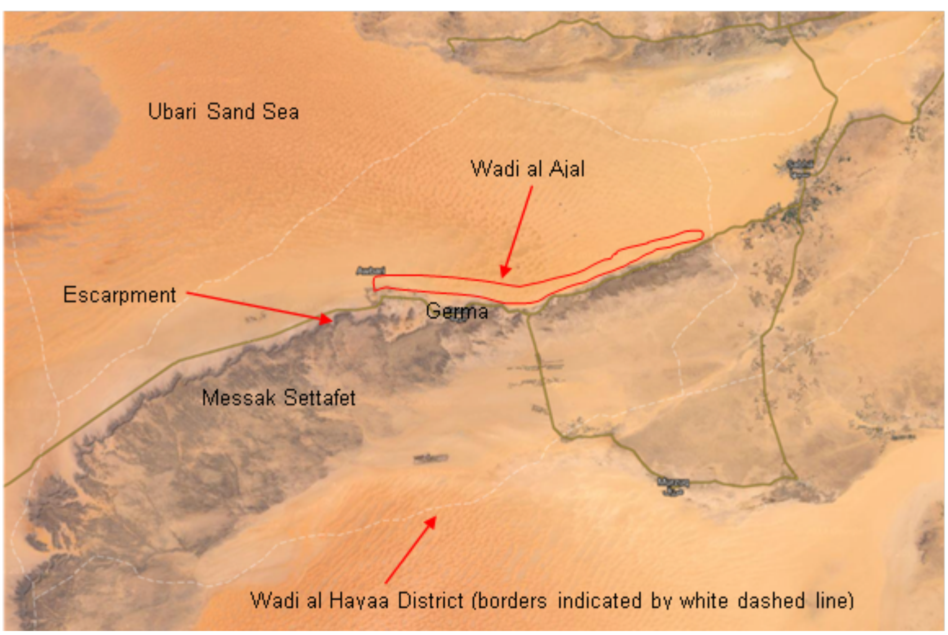

Figure 2. Landsat image of the focus area showing the location of Germa at the base of the Messak Settafet. Source https://www.google.com/maps.

the Cretaceous and containing valleys and a plateau with a ridge rising 300 meters that runs from the north to the west (Perego et al., 2011). The valleys began to form as early as the Late Tertiary due to an abundant water supply and continued to be shaped along with the ridge by degradation through weathering during the Paleogene (Perego et al., 2011). The geomorphological features originated during warm and rainy phases within the Tertiary, the interglacials within the Pleistocene, and the Holocene (Perego et al., 2011). The entire Messak is surrounded by dune fields (Perego et al., 2011). The most northern part of the Messak contains the area of focus found within the study. This section is called the black Messak in the Tuareg language because it is covered by hamada of angular rocks with a dark varnished surface (Perego et al., 2011). The dark varnishing color of the rocks is shown in Figure 3. The varnishing occurred within the Middle Holocene when the manganese

Figure 3. Some of the dark stony hamada contained within the Settafet part of the Messak. Source Perego et al. (2011).

component within the rock biomineralized as the environment became dryer (Perego et al., 2011). The area of interest contains desert pavement such as the hamada with some rock outcrops. There are areas of ephemeral fluvial drainage cutting through the hamada and slopes (Perego et al., 2011).

The study area has moderate to high relief because the escarpment is distinguished from the rest of the area by its color and change in elevation as it rises upslope as shown in Figure 4. The wadis occurring across the surface of the plateau, originated from weathering during the Plio-Pleistocene

Figure 4. A view of the escarpment from the valley bottom to the plateau top. Source Perego et al. (2011).

transition and some are quite deep (Perego et al., 2011). Toward the west, the valley bottom consists of fluvial sediment such as sand and gravel, which can be covered by aeolian sand (Perego et al., 2011). Along the steep walls of the wadis are gravel bars with large sized clast supported gravel as well as rounded boulders with engravings corresponding to the Neolithic or Early to Middle Holocene (Perego et al., 2011). The gravel was shaped and rounded when there was surface-water drainage during the wet times within the Upper Pleistocene until the area dried within the Holocene. The alluvial fan near the base of the escarpment provides groundwater for the present residents, while water for historical agricultural irrigation was obtained through qanats drawing from alluvial fans of the escarpment.

The narrow strip of land along the base of the escarpment was home to an ancient civilization known as the Garamantians and their capital city Garama, now known as Germa. Figure 5 shows the location of present-day Germa nestled at the base of the Messak Settafet ridge.

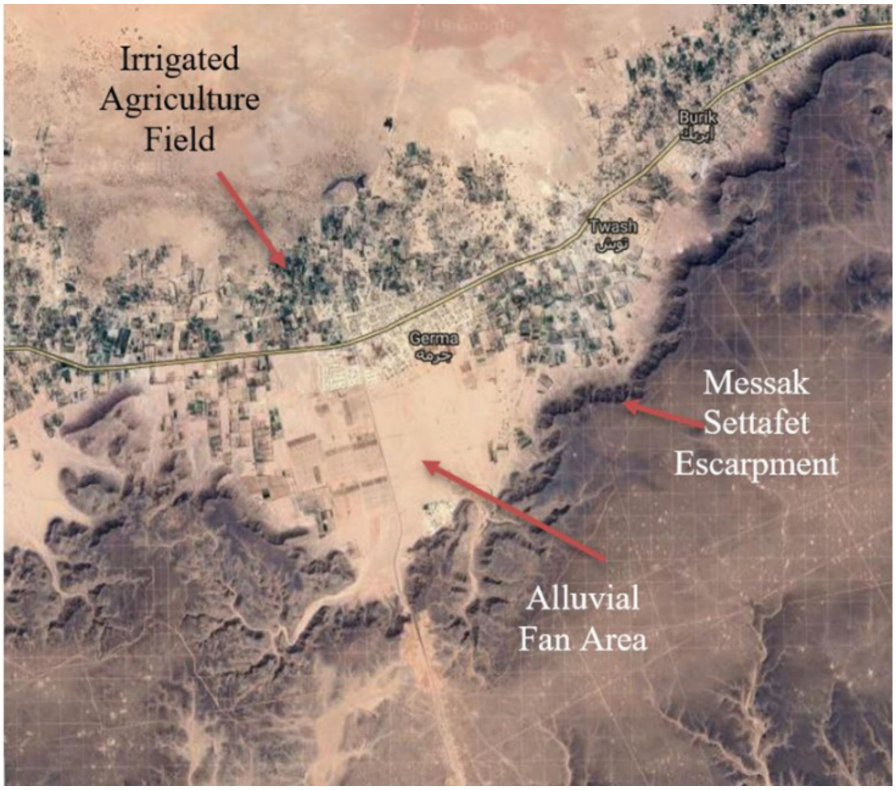

Figure 5. Landsat image of the present-day city of Germa and showing geologic features such as the Messak Settafet escarpment, the alluvial fan, and the green agriculture fields. Source https://www.google.com/maps.

Lithology

The Messak Settafet escarpment represents the westernmost edge of the Nubian Sandstone (Garcea, 1997). The Messak Sandstone Formation lies on top of the Jurassic Taouratine Formation, which consists of erodible cross-bedded sandstone with siltstone, shale, and conglomerate (Perego et al., 2011). When the eroded material gives way, it allows for some material at the top to fall to the base of the escarpment and within the valley. This material forms the talus and bare rock as well as glacis, which consists of all the other rock units interbedded with the sandstone. The lithology of the escarpment is shown in Figure 6.

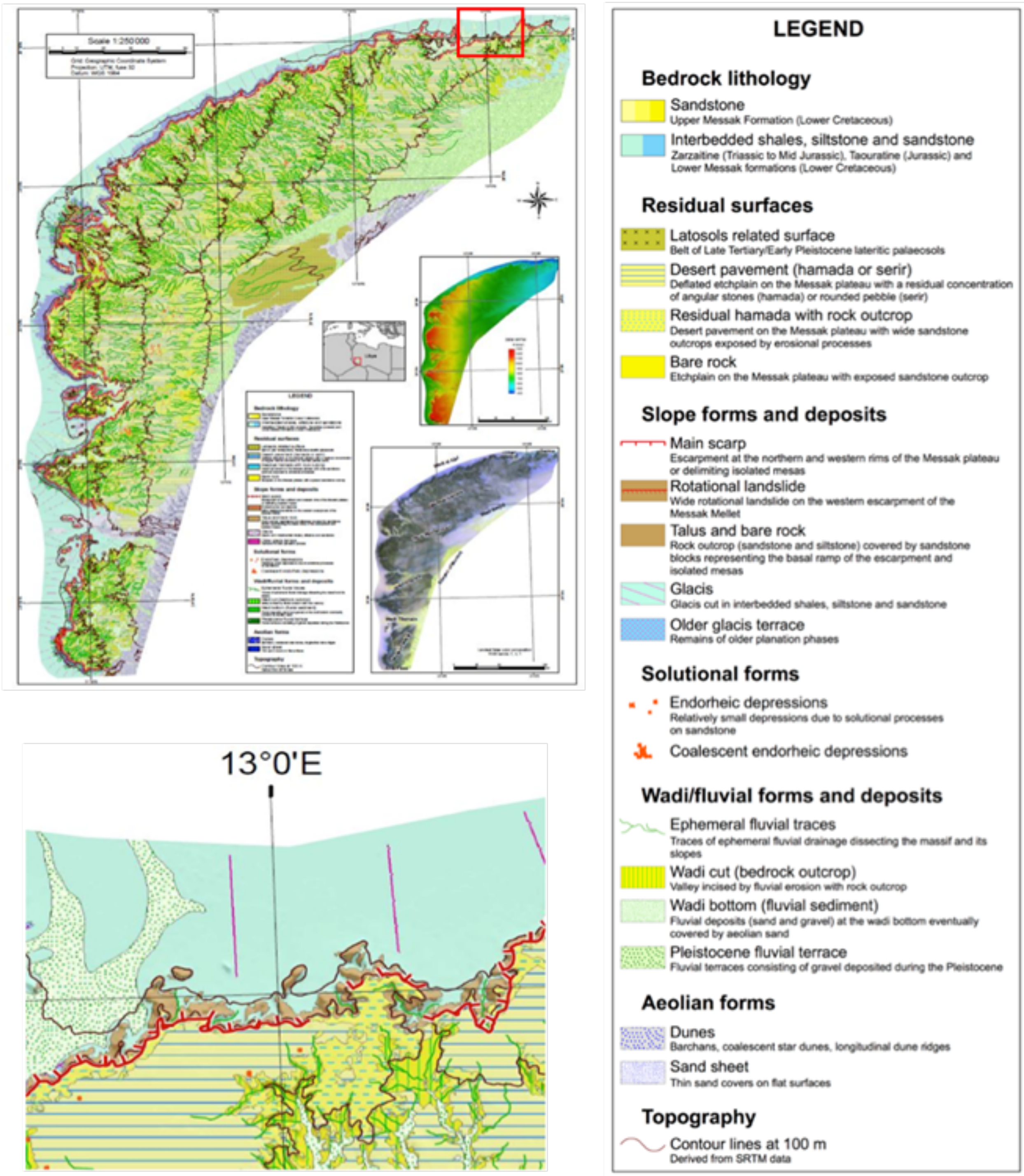

Figure 6. Geomorphological map of the Messak Settafet and Mellet in southwestern Libya. The study area is found within the red rectangle shown at top left. An enlarged view of this area is shown at bottom left and an enlarged view of the legend is shown on the right. Source Perego et al. (2011).

Climate and Hydrology

The modern climate of Fezzan is hyper-arid with negligible rainfall throughout much of the year. Most of the water within the study area is shallow groundwater associated with the escarpment. The few oases in the desert are located outside of the study area. While there are no rivers, there are relic traces of where water used to flow but has since moved underground. Most of the year, the temperature is about 22°C to 25°C and the rainfall is between 0 to 10 millimeters (Perego et al., 2011). The climate is dependent on the behavior of the ITCZ or Intertropical Convergence Zone, which deals with solar heating causing monsoons of rain in the summer followed by drought in the winter (Perego et al., 2011). Past climate conditions during the interglacial periods of the Quaternary were different from the present and may have been wetter based on evidence of higher water levels dating to the Early and Middle Holocene (Perego et al., 2011). Furthermore, there were humid periods during this time and the aquifer was last recharged during the Holocene African Humid Period (Perego et al., 2011).

History of Late Pleistocene-Holocene Climates

Paleoclimate

Throughout history, the many topographic features within the Sahara and the study area of Fezzan were shaped by the climate. The climate of present-day northern Africa is very different than that of the past. Compared to the whole geologic time frame, the climatic oscillations and events researched for this study are the most notable because they can be interpreted due to their proximate age to the present. The climate in northern Africa, including the study area, experienced major variability during the Pleistocene and Holocene. This time period was characterized by many periods of humidity throughout the Sahara (Skonieczny et al., 2015). These periods of humidity were offset with periods of aridity. One such dry event that occurred within the Holocene was known as the Younger Dryas (YD). This event occurred from 12,800 to 11,500 BP (Tierney et al., 2017). The YD predated the most recent humid period also referred to as an African Humid Period (AHP) focused within this study (Figure 7). This humid period occurred within the Early Holocene from 11,700-5,000 BP (Skonieczny et al., 2015). The climate of Africa was very different at that time. The

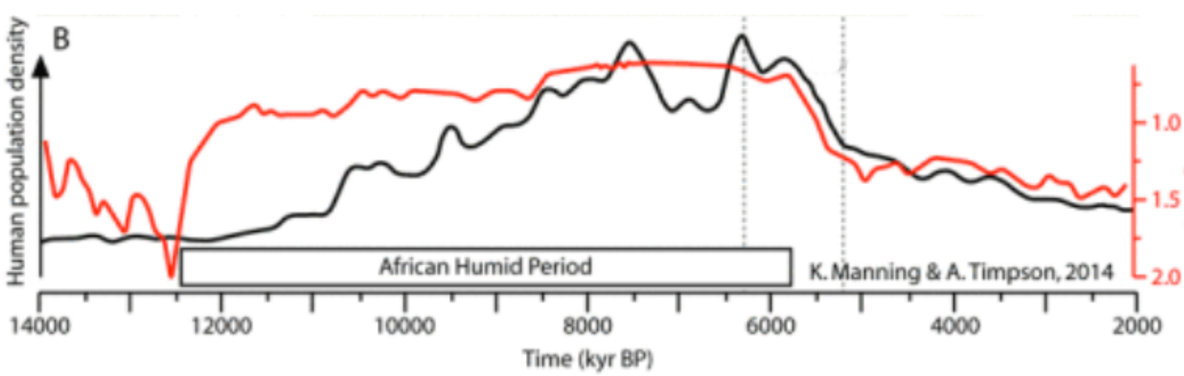

Figure 7. The relationship between population (black) and aridity (red) over the last 14,000 years and the timeline of the African Humid Period. Figure modified from Manning and Timpson (2014).

Sahara had lakes and most of the land was completely vegetated (deMenocal et al., 2000). The increase in humidity or rainfall also allowed for vegetation and population growth and transformed the arid land ranging from 19°N to roughly 31°N (Tierney et al., 2017). This Green Sahara phase eventually waned, and the Sahara returned to desert. Evidence suggests that the Green Sahara ended roughly 5000 years BP (Tierney et al., 2017). These changes in climate from life sustaining to aridity in both severity and area size of impact are so drastic that they are referred to as "climatic crises" (deMenocal et al., 2000).

It is difficult to explain why the climate shifted is difficult and many of the ideas are inferences. Some of the ideas and explanations sound scientifically correct enough to explain the phases of humidity and the phases of aridity. One argument is that external forcing mechanisms such as tectonic shifts, planetary orbital shifts, and subsequent insolation fluctuations affected the climate systems (Maslin and Christensen, 2007). Insolation is the amount of incoming solar radiation reaching an area of the Earth. The planetary cycles, such as Milankovitch cycles, are an external force that was responsible for these changes and climate shifts. Milankovitch cycles involve several behaviors of the Earth as it orbits around the sun. The three orbital factors of the Earth are the eccentricity, which is another way of saying how circular the orbit is, the obliquity which refers to the tilt of the axis of rotation and is responsible for Earth's seasonality, and finally, precession, which describes the Earth's axis of rotation (obliquity) in conjunction with the Earth's elliptical orbit (eccentricity) (Maslin and Christensen, 2007) as shown in Figure 8. When considering the Milankovitch cycles, it is important to understand how often their cycles last or occur. The change from circular to elliptical eccentricity cycle happens about every 96,000 to 125,000 years, the change in obliquity or tilt from 21.8° to 24.4° occurs about every 41,000 years, and finally the axis of rotation precession has a rotation axis period of about 27,000 years and precession change in Earth's elliptical orbit of about 105,000 years (Maslin and Christensen, 2007). The combination of these orbital factors makes up the Milankovitch cycles, which occur about every 23,000 years (Maslin and Christensen, 2007). The eccentricity has a relatively minor insolation effect but does influence seasonal variation (Maslin and Christensen, 2007). Obliquity, depending on which hemisphere is

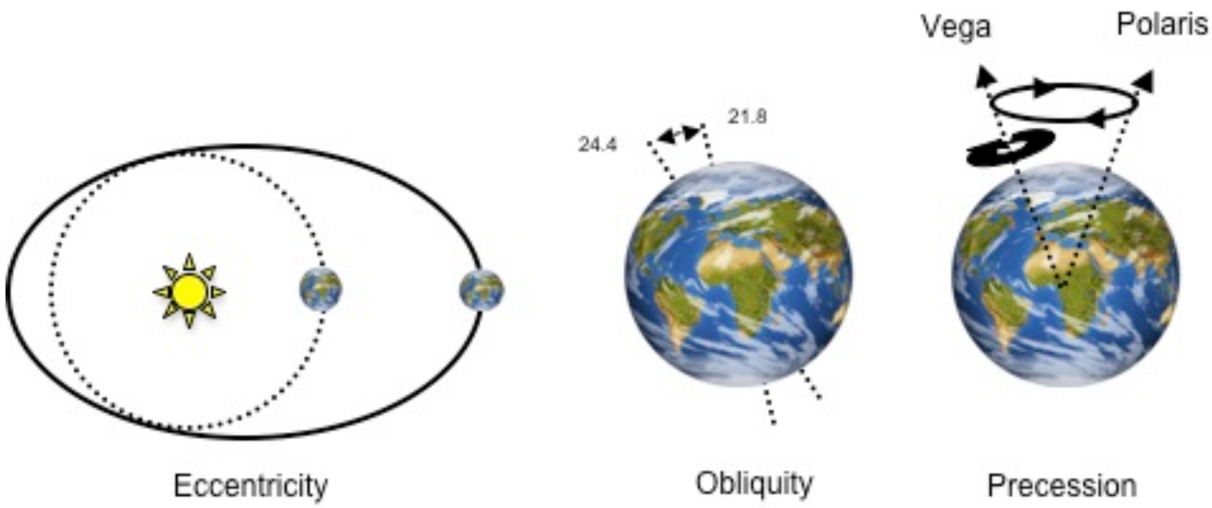

Figure 8. Main orbital components that make up the Milankovitch cycles of eccentricity, obliquity, and precession.

facing the sun, changes the amount and duration of insolation, which affects seasonal temperatures (Maslin and Christensen, 2007). It is not hard to imagine how changing any of these factors could have an influence on the climate of not just Africa, but the entire planet. Another external force involving a planetary factor that may have played a part occurred in the Early to Middle Holocene. Perihelion, when the Earth is closest to the sun, occurred in the northern sky of summer as opposed to the northern sky of winter as it is now (Coe and Bonan, 1997). This position of the Earth in relation to the sun during the Early to Middle Holocene resulted in increased insolation, which subsequently increased both the sea and land temperature and pressure gradient (Coe and Bonan, 1997). As a result, this led to increased moisture convergence leading to precipitation on northern Africa (Coe and Bonan, 1997). This interpretation explains how the change of just one factor can influence weather behaviors and cycles. The change in the precession affects the behavior of the African monsoon and the ITCZ because it increases the insolation and therefore, the ITCZ and monsoons shift northward (Figure 9) (Skonieczny et al., 2015). Internal forcing mechanisms such as the greenhouse effect, ocean circulation, and effects of heat and moisture transfer also affect the

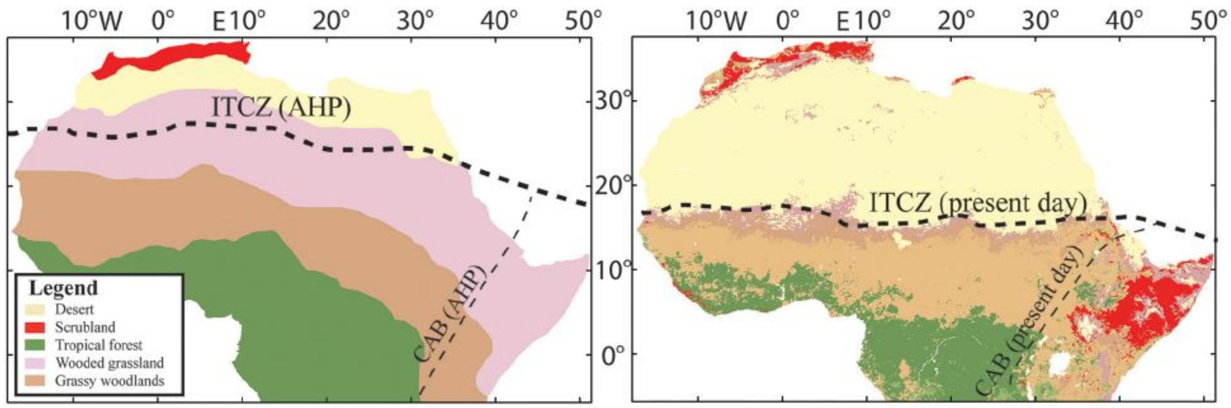

Figure 9. Illustration of how the southward shift of the Intertropical Convergence Zone (ITCZ) affected the climate of northern Africa. Source Wright (2017).

environment (Maslin and Christensen, 2007). Because land is a better heat conductor than oceans, insolation creates a low-pressure center over the land, which introduces moist winds and precipitation (deMenocal et al., 2000). This same process may have contributed to increased humidity during African Humid Periods.

Another planetary process that affects the climate is the impact of insolation on albedo (ability to reflect) and the subsequent positive feedback loop where one factor leads to another and eventually reinforces what started the process. The Milankovitch cycles are responsible for the glacial and interglacial cycles (Maslin and Christensen, 2007). Glaciation occurs when there is decreased summer insolation within the northern hemisphere thereby preventing ice from melting and instead, allowing it to accumulate (Maslin and Christensen, 2007). During the Last Glacial Maximum (LGM) about 18,000 years ago, glacial ice sheets were at their greatest coverage (Maslin and Christensen, 2007). The positive feedback began because the high albedo of ice decreased the insolation absorbed by the planet, which resulted in cooler temperatures and therefore, more ice formation (Maslin and Christensen, 2007). Another positive feedback loop occurs when ice sheets are massive enough to affect the atmosphere in such a way that storm paths are changed resulting in the reduction of warm water circulation into the northern hemisphere (Maslin and Christensen, 2007). This promotes cooler temperatures and allows for more ice growth (Maslin and Christensen, 2007).

However, there had to be other factors that would reverse this movement or shift the zones to the arid conditions seen today. About 8,200 years ago, the ice-dammed lakes in Canada melted, which produced a large inflow of freshwater to the Atlantic Ocean, resulting in cooler temperatures (Cremaschi et al., 2010). This led to less evaporation around northern Africa, which led to weaker monsoons and the ITCZ shifted southwards (Cremaschi et al., 2010). This may have happened due to the AMOC (Atlantic Meridional Overturning Circulation), which transports the warm upper portion of the Atlantic Ocean to the north and returns cold deeper waters to the south, thereby causing arid events in North Africa (Castaneda et al., 2009). AMOC is weakened from inflow of freshwater from higher latitudes, which causes cooler sea surface temperatures (Castaneda et al., 2009). This could have occurred from the melting of ice-dammed lakes mentioned previously. Cooler temperatures, along with strengthened northeastern trade winds, shifts the monsoons in North Africa southward resulting in desertification (Castaneda et al., 2009). Another example of an albedo positive feedback loop occurs when the process of desertification reinforces itself. The decreased precipitation reduced the vegetation cover thereby increasing the presence of sand, which has a higher albedo than vegetation (deMenocal, 2000). The higher surface (sand) albedo compared to that of darker vegetation reflects insolation causing the insolation to decrease, which results in less evaporation of surface water that would be used for precipitation and thus closes the feedback loop. When considering the possible explanations for the changing African climate, it could be any one of these explanations or a combination thereof.

Lakes

The orbital forces affecting the climate of Africa have been occurring over long periods of time. These forces that influenced climates contributed to the establishment of the mega lakes in northern Africa. During the Late Miocene, there were many factors such as tectonic and volcanic activity, and aridity around the Mediterranean Sea that led to expanded river systems because natural river flows were blocked (Drake et al., 2008). During times of increased humidity, the expanded rivers fed into basins to create lakes such as Lake Mega Chad (Drake et al., 2008). The estimated size of this lake was 361,000 km^2 (Drake et al., 2011). A similar occurrence is responsible for the origin of Lake Mega Fezzan during the Late Miocene (Drake et al., 2008). Volcanic activity blocked two rivers from flowing to the Mediterranean thereby creating a closed basin, which filled to form a lake during humid periods (Drake et al., 2008). During the Pliocene, additional volcanic activity expanded the basin where humid periods could also have created a larger lake (Drake et al., 2008). During the Pleistocene, the Fezzan Basin continued to expand, and the water within the basin was affected by the subsequent humid periods, which depended on moist interglacials and the arid times during the glacials (Drake et al., 2008).

An example of the glacial and interglacial timeline is shown in Figure 10. The interglacials also experienced increased pluvial periods which contributed to mega lake formation. During the

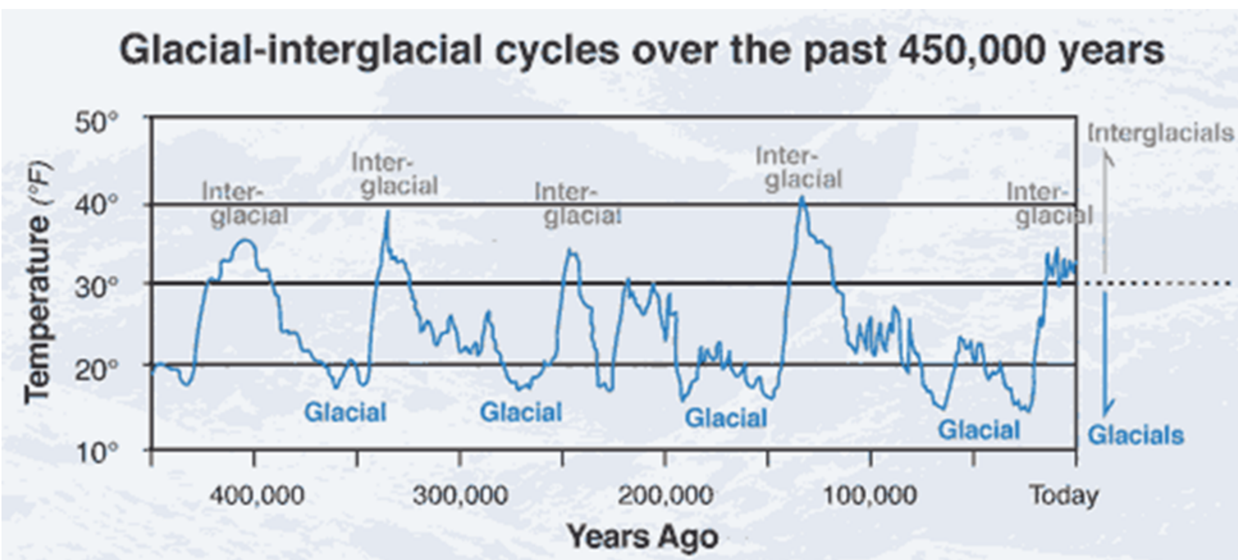

Figure 10. The glacial and interglacial periods of the past 400,000 years and their respective temperature fluctuations. Source https://geology.utah.gov.

Middle to Late Pleistocene interglacials (420,000 to 200,000 years ago), conditions were sufficiently moist to produce the giant Mega Fezzan lake with a size of about 135,000 km^2 (Drake et al., 2008). This large lake is shown in Figure 11. Within the Late Pleistocene and Holocene, there was

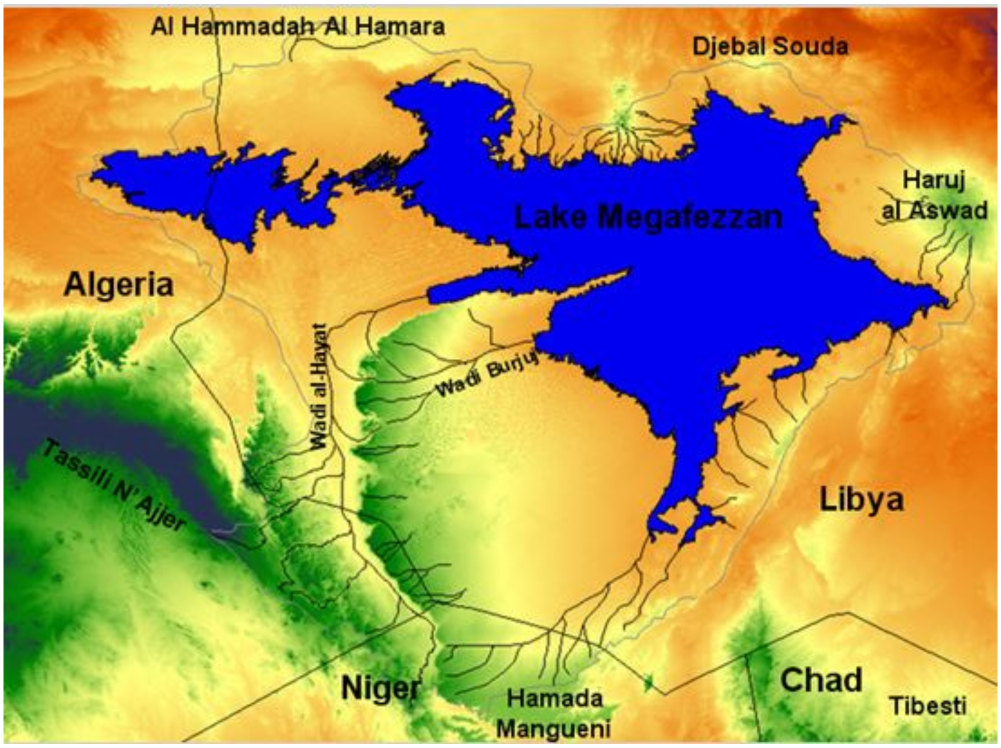

Figure 11. The likely location one of the mega lakes, Lake Mega Fezzan when it existed. The crescent shaped area in the center is the location of the Messak Settafet. Source http://www.kcl.ac.uk.

interglacial humidity in the Fezzan Basin especially during the last two interglacials (Drake et al., 2008). However, about 120,000 years ago, water availability was more limited during the humid interglacial periods, which ultimately resulted in a collection of smaller lakes rather than one mega lake (Drake et al., 2008). Essentially the lakes came and went, possibly not as large as they had previously, but it appears as though a time came when their classification as a mega lake ended at around 120,000 years ago. Although the time for the mega lakes ended, there have been times of humidity closer to the present that encouraged animals and people to spread onto the Sahara Desert due to the presence of rivers.

The Garamantians

The Messak (Amsak) Settafet or Sattafet plateau is known for the rock art that was engraved on the sides of valleys (Garcea, 1997). The presence of artifactual material, the rock art on the surface of the Messak, and lithics with an age between 6825±90 to 4565±165 years BP all suggest there were people at this area during the Pleistocene and Holocene (Garcea, 1997). This time-period coincides with the high stage lake levels in the study area. Within the valleys, lakes were at an intermediate level at about 8445±160 years BP and then dropped to their lowest point at 7325±130 years BP until 6625±100 years BP when the lakes rose to their highest level (Garcea, 1997). An abundance of lakes in the area at this time would have attracted people, and they could have contributed to the rock art and artifacts found there. When the last Green Sahara ended, the climate changed and the people who did not migrate to areas with a permanent water supply had to find other ways to survive. One such civilization was the Garamantians (Figure 12). This civilization lasted from 900 BC to 500 AD within the Wadi al Ajal area of the Fezzan region (Pelling, 2005). The people who made up this tribal

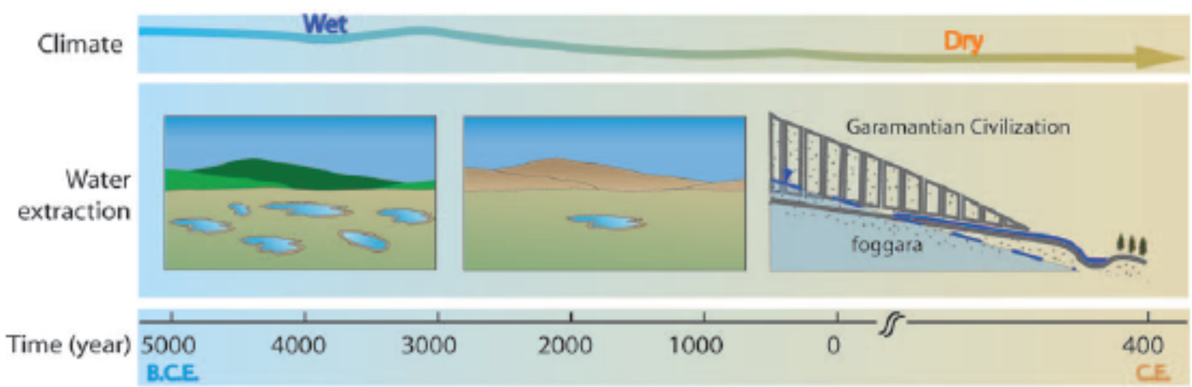

Figure 12. The climate transitioning from wet to dry accompanied by a timescale of the last 5400 years showing the emergence of the Garamante and the reliance on qanats as surface water disappeared. Source Schwartz and Ibaraki (2011).

civilization were Saharan pastoralists who traced their roots to Berbers (Keys, 2004). Initially thought of as desert barbarians who lived in a small area, research has shown they controlled several major towns with their capital known then as Garama (Keys, 2004). The Garamantians were able to survive by using tunnel technology adapted from Persia, known as foggaras in the Berber language, to extract groundwater (Keys, 2004). They used the foggara technology to access the water at the base of the escarpment at the Wadi al Ajal for the purpose of irrigation (Pelling, 2005). This technology for producing groundwater enabled the Garamantian Empire to expand and practice settled agriculture. This growth required a social and political change, which allowed their society to militarize to conquer and enslave other people living within the Sahara (Keys, 2004). By using slaves to construct more water tunnels, the Garamantians were able to expand their empire even more (Keys, 2004). Ultimately, by about 150 AD, their empire grew to encompass about 180,000 km^2 with a population of about 10,000 (Keys, 2004).

The capital city of Garama contained large stone buildings some of which could have been a temple or palace (Keys, 2004). The Garamantians lived in planned suburbs with many rectangular mud brick houses (Keys, 2004). Some of the artifacts found within the city provide clues as to the professions of the people living in the city such as glass making, manufacturing of textiles, and gem and metal working (Keys, 2004). While these possible professions contributed to the economy, the Garamantians were known as a material culture that imported luxury items with the main object of trade being slaves, either obtained as tributes or captured (Keys, 2004). The Garamantians were also influenced by other cultures such as the Romans to the north and Egyptians to the east. This is evident due to the discovery of a Roman bathhouse in Garama and, as well as stated earlier, water extraction tunnels from Persia (Keys, 2004). In addition to technology, the Garamantes also adopted much of their religion and burial traditions from Egypt. Their worship was based on the desert god Ammon, while their burials took place in small pyramids (Keys, 2004). In addition to the pyramids, the Garamantians also utilized mausoleums, a Roman tradition, to worship and pay tribute to their ancestors (Keys, 2004).

Equally important to the Garamantians were sources of water and animals. This is evident from the artifacts found and the extensive rock art on escarpments or petroglyphs on desert rocks (Keys, 2004). Next to the images was text carved using the Libyco-Berber script, their ancient writing script (Keys, 2004) as seen in Figure 13. The rock art visually supports their role as a military power, by depicting the Garamantians as an aggressive masculine society evident from men wielding weapons or hunting (Keys, 2004).

Figure 13. Rock art engravings of hunters, animals, and the ancient text. Source Barnett and Guagnin (2014).

Ultimately, the Garamantian Empire declined when their source of water ran out. By about 400 AD, they had extracted about 100 billion liters of water during their reign of power (Keys, 2004). To obtain more water, they would have needed to dig deeper tunnels, which meant they would have needed to acquire more slaves (Keys, 2004). However, their diminishing water supply caused disruption among their organized society which affected food production, leading to a reduced population and political instability, all of which made it logistically impossible to obtain more slaves (Keys, 2004). Once the desert kingdom began to decline, it was easy for them to break apart and be absorbed into other cultures (Keys, 2004). Their ability to survive for a millennium while their environment was drying out is a testament to their ingenuity and ability to adopt other methods from other cultures. They did this by adopting the Persian foggara, known as a qanat in the Fezzan region.

Qanats

Structure

Because qanats played such an important role in the longevity of the Garamantian Civilization, it is important to understand exactly what they are and how they work. Most of the land is desert, so it only makes sense the available water would be within the ground and would be obtainable by using extraction methods. The qanat is a gravity powered water supply system with an underground tunnel connected to vertical shafts, which range from the water table to the surface (Figure 14) (Luo et al., 2014). The word qanat is based on an ancient Semitic word meaning “to dig"

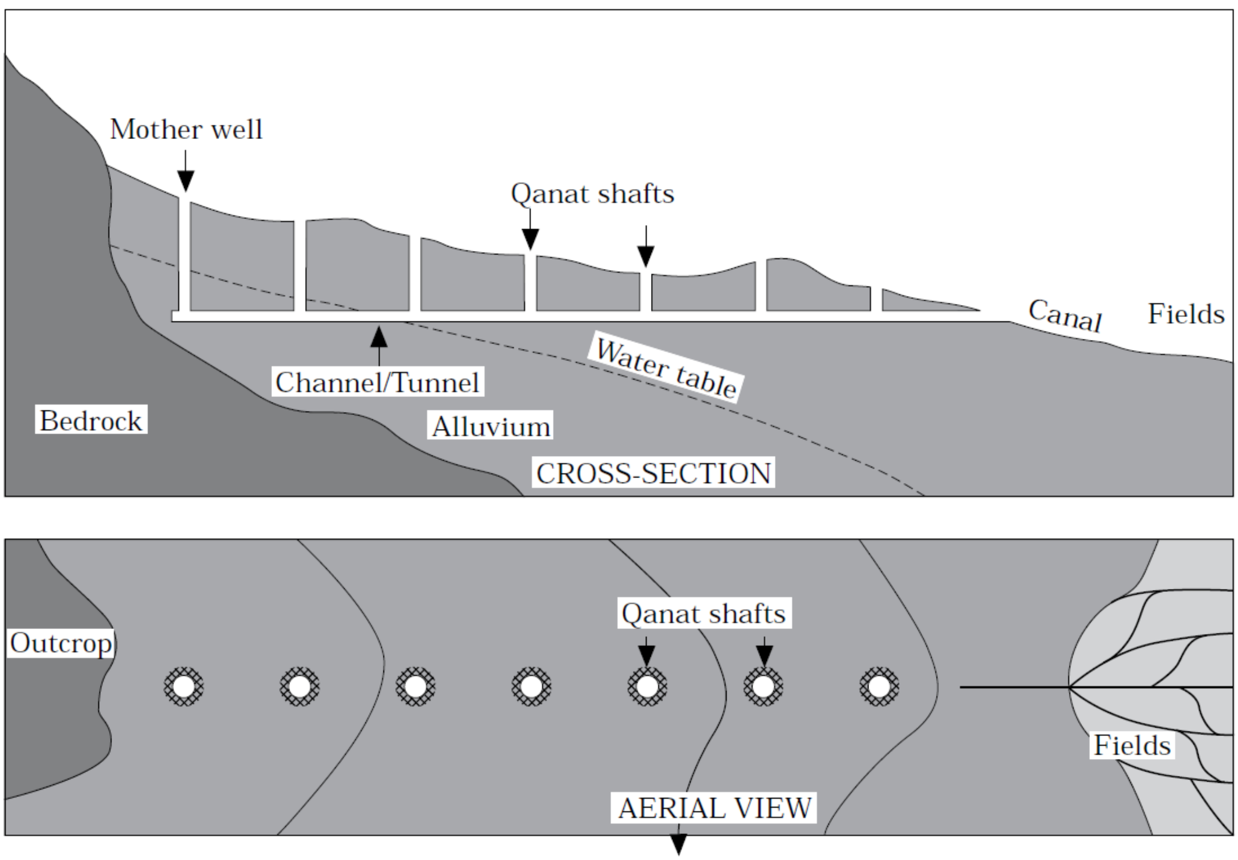

Figure 14. Cross-section and aerial view of a qanat, an ancient yet effective method of obtaining water in an arid environment such as those used in Germa. Source Lightfoot (1996).

(Shahraki et al., 2011). Several components compose the main structure of a qanat, and each has an important but different role. The mother well is located high up on the alluvial fan and is dug first mainly to determine where the water table is located (Cressey, 1958). The name "mother well" may have originated because this is the point that provided life to the qanat system or because it brought water and therefore life to the people who needed it. Digging then begins in the valley bottom and proceeds uphill to hit the water table and eventually the mother well (Shahraki et al., 2011). An underground sub-horizontal channel connects the vertical shafts to the mother well (Shahraki et al., 2011). The vertical shafts function as airshafts to provide oxygen for the workers and expedite the removal of sediments from the tunnel. The qanat is constructed by people digging the vertical shafts and horizontal tunnel by hand (English, 1968). During construction, material removed from the shafts (i.e., spoil) forms a circular mound around the top of the vertical shafts, which protect the vertical shafts from debris falling back down (Remini and Achour, 2013). Because the main access tunnel is below the ground surface, water can be transported tens of kilometers without loss due to evaporation (English, 1968). Qanats vary in length depending on the topography near them and how far the water needs to be transferred to reach its destination. In the study area, the qanats are short because of the steep alluvial fan along the escarpment. Qanats are usually built at places of higher elevation such as near mountains, and when they are built around mountains, the tunnels are short whereas they are longer in the desert regions (Beaumont, 1971). From an aerial perspective, qanats can be tracked because the spoil around the vertical shafts appear as a line of doughnuts on the ground surface (Cressey, 1958).

Function

Qanats are successful because of their design and how they operate. The near-horizontal tunnel starts out above the water table, but eventually passes through the water table higher on the alluvial fans. Groundwater from the alluvial fans flow into the gently sloping tunnel and runs downhill (Martinez-Santos and Martinez-Alfaro, 2014). The tunnel effectively conducts groundwater from a higher elevation to the outlet at a lower elevation where it can be used for irrigation (Beaumont, 1971). Water flow within qanats is a natural process. The only source of energy needed for qanats is gravity (Manuel et al., 2017). This is unlike many other methods of the day, which usually involved lifting water from rivers for irrigation using low capacity transfer systems. A benefit of using qanats is that they do not harm the environment (Manuel et al., 2017). It is thought that qanats are sustainable approaches for obtaining water in arid regions because they rely on gravity and do not upset the water balance (Lightfoot, 1996).

Maintenance

Although qanats are relatively low-cost systems and are considered low tech (Manuel et al., 2017), they do require routine maintenance and repair. Because qanats are often several kilometers in length, they can be costly to maintain which could lead to their destruction and abandonment (Martinez-Santos and Martinez-Alfaro, 2014). As stated earlier, the openings to the vertical shafts are surrounded or capped to prevent water contamination from silt and sand, however routine maintenance is still required to periodically clean the tunnels (Remini and Achour, 2013). Part of the maintenance involves removing invasive plants with long roots which, could block the path for the water (Remini and Achour, 2013). The capped openings also need maintenance to assure the prevention of material from mixing with the water. Capping the qanats lessens the need for frequent maintenance, which is good because performing maintenance in the tunnels is not always safe. Working around fast flowing water could wash the workers away or loosen the material which promotes cave-ins that would lead to loss of oxygen and ventilation resulting in suffocation (English, 1968).

The fact that qanats are underground does not save them from being damaged. They are prone to damage from earthquakes or lose their ability to flow due to calcareous deposits and the growth of other mineral deposits, which could lead to abandonment (Lightfoot, 1996). These two factors add to the constant maintenance issues. Drying of the climate, droughts, or over pumping may also reduce the flow from the tunnel due to a decline of the water table. Possible solutions would be to deepen the mother well and near-horizontal tunnel, or add branches to the main tunnel (Lightfoot, 1996). This would provide drainage below the new, lowered position of the water table.

Pumping

Across Africa and Asia, qanats are now mostly obsolete. They are dangerous to maintain and the water sharing ethic of past generations has been eroded. They are being replaced by high-capacity wells in the valleys on individual farms, which use the groundwater in an unsustainable manner. While generally more efficient, the result is declining water tables and an overall decline in groundwater storage (Manuel et al., 2017). One unfortunate outcome is that qanats lose their supply of water because the efficiency of motorized and pump wells lowers the water table (Beaumont, 1971).

Other factors driving the decline in qanats may not be just technology, but also the expanding scale at which technology is being used. For example, with population growth, even more pressure is being placed on irrigated agriculture to supply food for these countries. Newer technologies need to be found to address problems of groundwater sustainability. This is a challenging issue because sustainability in food is usually the top concern of countries compared to sustainability in water. Also, solving problems of groundwater sustainability requires high-end technical expertise and money, both of which are in short supply. Continued extraction of groundwater in hyper-arid regions of Libya without replenishment leads people to fear their water will be depleted (Faitouri and Sanford, 2015).

Concerns

Though the qanat is viewed as an environmentally friendly method of obtaining water, there are issues other than over pumping that are concerning. For example, while qanats can stretch many kilometers under the barren soil and make cultivation possible, over irrigating or having too many processes relying on water can lead to a decline in quantity of water (Lightfoot, 1996). In addition to concerns about the quantity of water, there are also concerns about the quality of water, which is important today because it contributes to the overall health and quality of life. Groundwater sources are disappearing around the world due to being over pumped and being contaminated through pollution (Schwartz and Ibaraki, 2011). The decline of available water from large aquifers can be attributed to mining groundwater and the demands from food production and a growing population (Schwartz and Ibaraki, 2011). While the wells can be deepened up to a point, there is a threshold beyond which qanats cannot be extended and retrieve water (Schwartz and Ibaraki, 2011). Increasing aridity toward the end of the Garamantes time eventually reduced the availability of water from the qanat system (Schwartz and Ibaraki, 2011).

These days, the drying of qanats is not mainly due to climate change but to modern water-well technology. In most arid regions, groundwater can be easily pumped out faster than it is being replenished (Schwartz and Ibaraki, 2011). Historically these factors were overcome with wetter times allowing for recharging, but with present negligible recharge and human intervention, depletion is possible (Schwartz and Ibaraki, 2011). Water may be the most readily available resource, but it is also the quickest to respond to a loss in its recharging factors such as rain or streamflow (Schwartz and Ibaraki, 2011). As a result of loss of water today, there could be scarcity of food, sickness, and declining of society (Schwartz and Ibaraki, 2011).

Qanat technology has been a sustainable approach that can provide a dependable water supply in desert environments lasting a millennium (English, 1968). A healthy qanat has a continuous flow from year to year and day and night which gives crops the water that they need (Lightfoot, 1996). While qanats were well suited for arid landscapes, now the combination of global climate change and huge groundwater overproduction will cause desert areas to become uninhabitable and contribute to the decline in qanats (Luo et al., 2014). This rampant overconsumption will accelerate with urban growth, and expanding irrigation (Luo et al., 2014).

Discussion

Determination of out the ages of the events discussed in this paper is not an exact science, and as such, some of the predicted dates of the events may differ among sources. Much of the uncertainty could be the result of erosion, which erased geological evidence pertaining to the timing of events. However, the tradeoff to the variety and range of the data or the number of sources reviewed, is that if most of the sources reach similar conclusions, then those dates are probably correct or close to being so. Based on all the sources, the dates of the events discussed in this paper do not differ that much.

The paleoclimate discussion showed that the African Humid Period collapsed over about 1000 years starting around 6000 years BP. The Sahara became dry with a trend towards even drier conditions evident moving to present-day (Figure 7). Time-wise, the Garamantian Empire blossomed during the driest times (about 2900 to 1500 years BP). Clearly, qanats and groundwater made a major contribution to the water-security of the Garamantes.

An important unanswered question is why qanats were capable of supplying water under the evident hyper-arid conditions prevailing in the Sahara about 2900 years BP. The classical qanat systems of Iran are associated with large alluvial fans occurring at the base of relatively tall mountains. Under cooler winter conditions with somewhat higher precipitation, moisture is stored as snow and is released as melt-water in early spring or directly as rain to the fans. The main point is that although alluvial fans are relatively large volume-wise, this annual pulse of recharge is required to provide an annual supply of groundwater for irrigation and other uses.

By comparison, the alluvial fans forming along the northwestern edge of the Messak Settafet escarpment are small and steep. The main reason is that the escarpment has a relatively small relief of about 300 m. Unlike the classical Iranian qanats, it is not likely that enough recharge would have been available on a seasonal basis every year during Garamantian times. Also, from a groundwater-storage perspective, such unconfined aquifers would have small overall storage capacities. High gradients also would tend to move water quickly through the fan and into valley sediments.

There are good arguments to be made that these qanats of the Fezzan operate in a unique manner that is distinctly different than those in Iran. It is likely then that groundwater storage is not provided by the alluvial fans but by the rocks of the Messak Settafet escarpment. In places, the escarpment is about 70 km wide. Details of the hydraulic properties are lacking but one could expect some combination of primary porosity and secondary porosity due to fracturing. What remains to be established is when the groundwater within the escarpment was recharged. Given the physical size of this fractured Messak Settafet aquifer, it is possible to envision that recharge during the African Humid Period would have remained stored for thousands of years, because of long adjustment time lags needed for flow systems to readjust to much smaller rates of recharge.

The shape of the escarpment appears conducive in facilitating recharge. Imagery (e.g., Figure 5) shows well developed surface-water drainage networks on the top of the escarpment. Because the top of the escarpment slopes to the southeast, surface water moves across the entire width of the escarpment rather than quickly flowing off across the steep northwestern slope (e.g., around Germa). Moreover, exposed fractured rock is particularly helpful for efficient recharge because infiltration can move downward out of the zone of intense evaporation.

This escarpment surface suggests another possibility for maintaining a groundwater system in an arid setting. Experience at Yucca Mountain in Nevada found that rare extreme events can produce runoff occasionally. So, with an efficient recharge setting, this process could be important.

More work is needed but it is likely that groundwater from the escarpment mostly flows northwest into the wadi system at its base. Topographically, the elevation at the base of the steep face of the escarpment (i.e., around Germa) is lower than the southeastern side of the escarpment, resulting in a groundwater divide that is pushed towards the southeast. Evidence of persistent groundwater flow away from the steep escarpment face is reflected in the presence of saline lakes hidden among the dunes towards the Ubari Sand Sea. The qanats of the Garamantians were likely intercepting some of this more permanent groundwater flow out of the Messak Settafet escarpment.

It is well known that the Garamantian Empire thrived largely because the knowledge associated with earlier discovery of qanat technology in Persia, which made its way along the historical trading routes across North Africa. However, this condition was necessary but not enough. Water security for the Garamantes also required a fluctuating climate system that provided timely recharge to the permeable bedrock of the Messak Settafet escarpment. An amazing collection of circumstances aligned at this time and this place in the Fezzan.

By understanding the past civilizations and history of the Sahara region of Africa, information can be gained that provides insight into what is happening in the present and may happen in the future. There are many issues in the world today that people in first world countries are not only unaware of, but also unaware of how serious those issues are. Basic human rights such as enough food and clean water are not found everywhere and people around the world are dehydrated, suffering, or hungry. Although these conditions have existed for a while, a new threat has emerged: global warming and climate change. Due to human actions, the world is experiencing changes such as rising sea levels, animal extinctions, and rising temperatures. There were forces in the past that also still occur today, such as the Milankovitch cycles or other planetary behaviors responsible for affecting the climate, and those forces may occur again resulting in similar changes. This time, however, the changes are compounded by the actions of humans.

Based on the findings of this study, though climate change may be inevitable, humanity should continue to seek ways to minimize their impact and adapt to the changes. This could be achieved by looking to qanats as an inspiration for adopting environmentally friendly methods because they operate solely on gravity. There are many different environments where the implementation of qanats would be beneficial. One such environment would be arid locations where there may be more groundwater rather than surface water. This would be especially helpful in areas of the world that are less developed and, because they may not have access to modern technology, such as motorized pumps, qanats would be an environmentally sustainable option.

Unfortunately for the most populous countries of the world in arid settings (e.g., Iran or Pakistan), the "train has left the station." The food necessary to feed these rapidly growing populations requires exploitation of aquifers in the valley bottoms using high capacity pumps. In most cases the associated drawdowns effectively dewater the up-gradient parts of the groundwater system where the qanats reside. The loss of qanats effectively means the wonderful self-regulating, sustainable water resource systems of the past are replaced by unsustainable water systems.

If the current unsustainable approaches to groundwater continue, combined with the threat of climate change, a very bleak future could be created for the continent of Africa and its citizens. In today's Sahara, many people use motorized pumps to extract their water, and while this is an easy way to obtain water, there is a risk that the amount of water extracted is more than the amount of water going back into the water supply. If this continues, water in Africa would no longer be a resource and Africa would need to rely on importation, which is not feasible in most settings. This will invariably lead to the abandonment of small villages and settlements in arid areas.

There is little room for hope, as the issues humanity is facing today may be insolvable. There is every prospect for a messy end game without an ability to cultivate and to develop agriculture that is sustainable and does not overdraw water resources.

Conclusions

In conclusion, the city of Germa within the Fezzan region of Libya provides clues and insight on how to live in an arid environment such as the Sahara. The people living here today have generally abandoned the sustainable water works that served civilizations before them so well. There is rock art found in this area that depicts both the people and the animals that once lived there. The Garamantians were one such civilization that was able to sustain their empire for a thousand years. The Garamantians managed to survive so long by using the Persian idea of foggara, also referred to as qanats. This technology consists of a sub horizontal underground tunnel for water to flow from underground aquifers via gravity in order to be used for irrigation and agriculture.

Today, the people living within Germa obtain their water through wells located in the valley at the base of the Messak Settafet escarpment next to their city. However, these modern water extraction practices, which rely on motorized pumps, threaten to drawdown groundwater substantially and to deplete aquifers. The qanats are largely in disrepair because few are willing to crawl around in unlined tunnels that commonly collapse.

The Garamantian Empire declined eventually due to a falling water table, so the consequences of humanity's practices are real. Much of the underground water in this area originated in the Late Pleistocene and Holocene and is rare and is hard to replace. Some of this water may be very old groundwater associated with the lakes such as Lake Mega Fezzan whose presence and levels fluctuated between times of aridity and humidity with the latter known as a Green Sahara or an African Humid Period.

The fluctuations in lakes and climate were the result of many factors. The most influential factor was the Milankovitch cycles which changes the insolation that Earth receives. Changing the insolation even a small degree caused the glacial and interglacial periods which formed the lakes.

Other planetary forces helped shape the climate, which is covered in this study. When ice dammed lakes in the northern hemisphere melted, this influx of freshwater weakened the AMOC and cooled the ocean waters, which affected the ITCZ and subsequently the monsoons. The location of the ITCZ determines where the monsoon precipitation occurs, and the Green Sahara of the Late Pleistocene and Early Holocene owed its existence to how north the ITCZ was at that time. When the ITCZ shifted southward, the Sahara as it is known today was formed. Current issues with global warming and climate change parallel the past. This study can help find environmentally sustaining ways for humanity to survive now. If all else fails, humanity could wait for the factors that led to the Green Sahara to return and possibly help make Africa green again. This option is why humanity is studying the Fezzan area very thoroughly. This ultimately means that this option might take a lot of time, and meanwhile, the effects could become worse or irreversible. Despite the bleak future that may come, qanats offer some light at the end of the tunnel.

Recommendations for Future Work

Though many areas could be explored for future work, elaborating features of the hydrogeological setting in the Libyan Sahara is one of the most important. Work of this kind is essential to understand fully why the qanat systems there functioned so successfully. Progress in such efforts will be difficult because there are almost no relevant previous hydrogeological investigations in this area and field access is impossible given the turmoil of Libya. Oil exploration that has gone on across southern Libya might be a source of geological data for some of the shallow bedrock units.

The most practical approach would be to couple space-borne remote sensing with regional hydrogeological modeling. Such an approach would make it possible to test a few of the hypotheses that were outlined in the discussion section. On a smaller scale, there are obvious remnants of qanats present in the vicinity of Germa that could be mapped with high resolution optical imagery. This would require higher resolution imagery than is presently available from products such as Google Earth. Remote sensed qanat mapping could be supplemented by the on-ground maps prepared previously by archaeologists. These data, used together with high-resolution digital elevation modeling, would make it possible to infer the approximate position of the water table and the geometry of the alluvial fans.

Another potential area of study is concerned with the sustainability of groundwater in arid countries such as Iran. The widespread demise of qanat systems across Iran with the development of high capacity alluvial wells has enormous implications for the future of these countries. In effect, an eminently sustainable approach to managing groundwater is being replaced by a largely unsustainable scheme that is guaranteed to provide short term gain in exchange for long-term loss.

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